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Performance investigation of an integrated wind energy system for co-generation of power and hydrogen

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ABSTRACT

In this paper, a wind turbine energy system is integrated with a hydrogen fuel cell and proton exchange membrane electrolyzer to provide electricity and heat to a community of households. Different cases for varying wind speeds are taken into consideration. Wind turbines meet the electricity demand when there is sufficient wind speed available. During high wind speeds, the excess electricity generated is supplied to the electrolyzer to produce hydrogen which is stored in a storage tank. It is later utilized in the fuel cell to provide electricity during periods of low wind speeds to overcome the shortage of electricity supply. The fuel cell operates during high demand conditions and provides electricity and heat for the residential application. The overall efficiency of the system is calculated at different wind speeds. The overall energy and exergy efficiencies at a wind speed 5 m/s are then found to be 20.2% and 21.2% respectively.

Introduction

The increasing energy demand for residential buildings and use of fossil fuels to meet these demands are having a substantial environmental impact. The use of renewable energy sources is attracting more attention as a replacement of other sources like fossil fuels. The main reasons are diminishing fossil fuel sources, global warming and CO_2 gas emissions. Clean and sustainable energy solutions for present and future requirements are renewable energy sources. The fundamental energy sources like solar, wind, geothermal and hydro are renewable because these sources are not depleted [1–5].

Zafar and Dincer [6] designed a renewable energy hybrid system consisting of PV panels and wind turbines for some useful outputs like hydrogen production, hot water and electricity. The exergoeconomic analysis is conducted to study the system performance under different environmental and operating conditions. It suggested an improved system when heat from a fuel cell is utilized to heat the domestic water. Kaabeche et al. [7] presented a system of combined wind and solar sources. It followed the power supply and deficiency by utilizing iterative optimization techniques.

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Ozlu and Dincer [8] investigated a hybrid system based on solar and wind sources and performed an exergoenvironmental and exergoeconomic analysis. The study calculated the number of houses in Toronto where the system can provide the supply. In the multigeneration system, the efficiencies are higher than the single energy systems. Tina and Gagliano [9] modeled a system based on the wind speed data and probabilistic solar irradiance and found the designed input of a pre-processing stage. The different types of wind turbines and their thermodynamic limits are studied and also reported for different wind energy plants [1].

Cao et al. [10] investigated a Ti–Cr–Mn system for potential applications to hybrid storage devices. The effects on the hydrogen storage properties were investigated by partial replacement of Cr by Mo and W and Ti by Zr. The alloy combination of $(Ti_{0.85}Zr_{0.15})_{1.1}Cr_{0.9}Mo_{0.1}Mn$ showed the best overall properties among the alloys with an H_2 desorption pressure of 9.54 atm and capacity of 1.78 wt%. Cao et al. [11] investigated a combination of Zr–Fe–V-based alloys for hybrid storage devices. The composition $(Zr_{0.7}Ti_{0.3})_{1.04}Fe_{1.8}V_{0.2}$ showed the best properties among these alloys with a H_2 desorption pressure of 11.2 atm and capacity of 1.51 wt%.

Aziz [12] demonstrated a load frequency control system by fluctuating the power of a wind turbine due to the fluctuation in wind speeds and explained that power generation is required to be compensated with some other controllable source. It was concluded that the combination of wind control area and base load plant provide better performance as compared to the combination of wind control area and peak load plant. Notton et al. [13] studied remote locations for wind and solar hybrid systems. The temporal complementarity of wind and solar sources is discussed for five different sites in the Mediterranean islands. The profitability and sizing of two selected sites are compared.

Amer et al. [14] studied a system design for Missouri University of Science and Technology, consisting of a power system, for combined heat and hydrogen, which was achieved by methane using a fuel cell. A resource availability and energy flow study was conducted to identify the source of feedstock which is required for the fuel cell to operate at maximum capacity. It was concluded that this combined system reduced the greenhouse gas emissions and fossil fuel utilization for the university design. Pade et al. [15] considered the challenges faced by fuel cell technology for residential purposes and conducted a study of different challenges like energy prices, heating demand, ownership structures, support scheme and electricity demand in three countries – Portugal, France and Denmark.

Sahin [16] presented a study on recent progress in renewable energy sources and specifically wind energy implementation in various industries. This study reported on wind energy history, wind-turbine technology, wind-power meteorology, wind-hybrid applications, wind energy economics, and various installed wind energy systems. Khare et al. [17] presented a review paper on hybrid renewable energy systems. The continuously increasing global energy demand is difficult to be met by non-renewable sources because of the environmental impact. Hybrid energy systems are a combination of two or more renewable energy sources. This primary objective of the review paper was to study the various aspects of hybrid renewable energy systems. The review paper also considered a feasibility analysis, modeling, control aspects, optimum sizing, reliability issues and also evolutionary techniques in renewable energy.

Carmo et al. [18] presented a comprehensive study on water electrolysis by proton exchange membrane (PEM) electrolysis. Hydrogen storage is considered as one of the best means to store the energy produced from various sources and a proton exchanger membrane electrolyzer provides a continuous solution of hydrogen production. Some challenges regarding electro-catalysts, current collectors, solid electrolytes and modeling efforts are also addressed in this study. The study provided new research directions to expand PEM electrolysis commercially.

Wang et al. [19] presented a parametric study on the performance of proton exchange membrane (PEM) fuel cells. The experimental effects of various operating parameters on the PEM fuel cell performance using hydrogen at the anode and air at the cathode were studied. Several experiments were conducted by varying the operating parameters like temperature of fuel cell, operating pressures, humidification temperature on the cathode and anode and several other combinations in order to analyze the PEM fuel cell performance. A three-dimensional fuel cell is also modeled in this study and comparisons with experimental data are also presented.

Takeichi et al. [20] introduced a hybrid hydrogen storage vessel. The potential of a novel high-pressure H_2 storage vessel combined with an aluminum-carbon reinforced plastic composite is described including the hydrogen storage system weight and volume for 5 kg of hydrogen. The study concluded that conventional hydrogen storage techniques can be replaced by a hydrogen storage system in terms of both gravimetric and volumetric hydrogen density. This hybrid hydrogen storage vessel requires a high volumetric hydrogen density, gravimetric density and hydrogen pressure.

Zafar and Dincer [21] introduced a hybrid system consisting of PV/T and fuel cells for the purpose of producing electricity and heat for the residential applications. The hydrogen is produced by an electrolyzer utilizing the excess power. The fuel cell will be operated when the power demand will be higher and the fuel cell will produce electricity, water and heat. Zhang et al. [22] proposed a hybrid system which comprises a high-temperature fuel-cell like molten carbonate fuel cell and solid oxide fuel cell, and heat engines like Brayton, Diesel and Carnot engines. The main irreversible losses which exist in heat engines and fuel cells are investigated.

Ezzat and Dincer [23] studied a new hybrid system which consists of a photovoltaic-fuel cell and Li-icon battery and compared this system with the base system consisting of a PEM fuel cell and Li-ion battery. They investigated the effects when the system is exposed to the photovoltaic arrays and also its effect on the energy and exergy efficiencies of the overall system. Xie et al. [24] discussed that the combined heat and power (CPH) system based on a fuel cell as an efficient means of overcoming residential energy requirements in terms of cost if the cost target can be met. A micro-CPH system is designed in Aspen Plus which produces 1 kW of electricity. It was found that the energy associated with the unused streams is the main cause of exergy and energy losses. Zabalza et al. [25] presented a feasibility study for fuel cell

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